

Improving the accounting of field emissions in the carbon footprint of agricultural products: a comparison of default IPCC methods with readily available medium-effort modeling approaches

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Abstract

Purpose The estimations of greenhouse gas (GHG) field emissions from fertilization and soil carbon changes are challenges associated with calculating the carbon footprint (CFP) of agricultural products. At the regional level, the IPCC Guidelines for National Greenhouse Gas Inventories (2006a) Tier 1 approach, based on default emission factors, insufficiently accounts for emission variability resulting from pedo-climatic conditions or management practices. However, Tier 2 and 3 approaches are usually considered too complex to be practicable. In this paper, we discuss different readily available medium-effort methods to improve the accuracy of GHG emission estimates.

Methods We present four case studies—two wheat crops in Germany and two peach orchards in Italy—to test the performance of Tier 1, 2, and 3 methodologies and compare the estimated results with available field measurements. The methodologies selected at Tier 2 and Tier 3 level are characterized by simple implementation and data collection, for

which only a medium level of effort for stakeholders is required. The Tier 2 method consists of calculating direct and indirect N₂O, emissions from fertilization with a multivariate empirical model which accounts for pedo-climatic and crop management conditions. The Tier 3 method entails simulation of soil carbon stock change using the Rothamsted carbon model.

Results and discussion Relevant differences were found among the tested methodologies: in all case studies, the Tier 1 approach exceeded the Tier 2 estimations for fertilizer-induced emissions (up to +50 %) and the measurements. Using this higher Tier approach reduced the estimated CFP calculation of annual crops by 4 and 21 % and that of the perennial crop by 7 %. Removals related to positive soil carbon change calculated using the Tier 1 approach also exceeded the Tier 3 calculations for the studied annual crops (up to +90 %) but considerably underrated the Tier 3 estimations and measurements for perennial crops (−75 %). In this case, the impact of the selected Tier method on the final CFP results was even more relevant: an increase of 194 and 88 % for the studied annual crops and a decrease of 67 % for the perennial crop case study.

Conclusions The use of higher Tiers for the estimation of land-based emissions is strongly recommended to improve the accuracy of the CFP results. The suggested medium-effort methods tested in this study represent a good compromise between complexity reduction and accuracy improvement and can be considered reliable for the assessment of GHG mitigation potentials.

Keywords Carbon footprint · Crop management · Fertilizer field emissions · GHG accounting · Regional variability · Soil carbon change · Tier methodologies

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1 Introduction

Agriculture accounts for one third of global greenhouse gas (GHG) emissions (Lal and Kimble 1997). If demand for food and biomasses continues to increase, annual GHG emissions from agriculture may increase proportionally, along with the vulnerability of agro-ecosystems to climate change (Xiong and Khalil 2009). However, agriculture also has a significant potential to reduce GHG emissions, as soils are the second largest carbon (C) sink after oceans (Lal and Kimble 1997). In general, there are three options for climate change mitigation in agriculture. First, GHG emissions can be reduced by improving the management of C and nitrogen (N) flows in agro-ecosystems. Second, increasing the level of temporary C storage through improved agricultural management practices can increase soil C sequestration. Third, the replacement of fossil fuels with renewable fuels such as residues from agricultural crop production also is possible.

During the last decade, the interest of companies and policy-makers in carbon footprint (CFP) as a supporting tool to assess the impact of food and biomass production on global warming processes and as a tool to design impact reduction plans has grown steadily.

Based on the completeness principle stated in ISO 14067 (2013), the most recent international reference standard about CFP, all GHG emissions and removals that provide a significant contribution to the CFP of the analyzed product system should be included in the study.

Although field emissions from fertilization and crop residue management (CO_2 and N_2O) can contribute considerably to the GHG balance of food and bioenergy products, they are often disregarded in CFP studies (Bessou et al. 2013). The same applies to CO_2 fluxes occurring due to changes in soil C stocks subsequent to crop management change (Brentrup et al. 2000; Petersen et al. 2013), which, following the ISO 14067 (2013), should be included in CFP if not already calculated as part of land use change.

For the accounting of field emissions at country level, the IPCC guidelines for National GHG Inventories (IPCC 2006a) provide, in the fourth volume dedicated to Agriculture, Forestry and Other Land Use sector (AFOLU), three calculation pathways (Tiers) characterized by different degrees of complexity: Tier 1 includes low-accuracy methodologies, which can be applied by using the default emission factors provided by the IPCC; Tier 2 methodologies require the use of national emission factors reflecting local pedo-climatic characteristics; finally, Tier 3 methodologies are based on model simulations or in situ measurements. Tiers 2 and 3 are referred to as the higher Tiers in the following text.

At present, the most common practice is using Tier 1 methodologies for field emission calculation in life cycle assessment (LCA) and carbon footprinting of food and energy crops. However, Tier 1 methodologies are intended for use at large

spatial scales, and they can generate substantial errors in predictions at finer spatial scales. In fact, at regional and sub-regional levels, Tier 1 methods are not always sufficiently accurate to account for the spatial variability of GHG emissions due to different soil, climate, and management practices. Conversely, higher Tiers (Tiers 2 and 3) are usually considered too complex and time-consuming to be practicable in the development of LCA studies. Therefore, the IPCC guidelines recommend using a higher Tier for the key emission categories and provide decision trees to support identification of the most suitable Tier.

There is an urgent need for the application and validation of appropriate higher tier methodologies at farm, project, or plantation scales, to address local issues with bioenergy and food sustainability and identify local mitigation potentials (Smith et al. 2007; Smith et al. 2012).

The aim of the present paper is to provide to CFP practitioners higher Tier methods “readily available” and “easy to implement” (with a medium effort) to assess field emissions from fertilization and from soil carbon change consequent to crop management change for the inclusion into CFP assessment studies of agricultural products. We selected higher Tier methods which match these requirements, choosing the Tier 2 method based on the Bouwman et al. (2002a, b) approach for estimating field emissions from fertilization and the Tier 3 method for soil organic carbon (SOC) change assessment based on simulations with the Rothamsted C (RothC) model (Coleman et al. 1997); both methods are described, respectively, in Sects. 2.2 and 2.3. These methods have been applied to four case studies and compared with Tier 1 results and with measurements, in order to test their performance. The measurements were not intended to be used as Tier 3 approach, because they are not always readily available for LCA practitioners, but could be used to confirm the validity of the model for the examined agro-ecosystem conditions.

A further goal of the paper is to assess and compare the influence of the variability of regional inventory data on CFP results, depending on the adoption of Tier 1, Tier 2, or Tier 3 assessment methods. The examined case studies, two winter wheat crops in Germany and two peach orchards in Italy, are described in Sect. 2.1. The case studies were deliberately selected to represent different soil characteristics, climate conditions, and crop types (annual and perennial) in order to test how the different methodologies handle this variability.

2 Materials and methods

2.1 Field experiments

Four field trials were selected based on crop type (annual crops and perennial crops), soil, and climate conditions. Characteristics of all sites are presented in Table 2. While we

assumed that no land use change occurred in our case studies, there were confirmed changes of the crop management practices.

The two winter wheat crops were cultivated at two different sites in Germany (sites 1 and 2) and for 2 years (2011–2012 and 2012–2013). They were sown after plowing at the end of September and harvested the following summer (end of June). Both cropping systems were rain fed. Site-specific rates of N fertilization were calculated based on field-sampled soil mineral N content in springtime and crop-specific target values from the official recommendation system, which reflects expected crop N uptake during the season, and split into 50 % mineral (calcium ammonium nitrate applied in cultivation period 2011–2012: 101 kg N ha⁻¹ at site 1 and 73 kg N ha⁻¹ at site 2 and in period 2012–2013: 105 kg N ha⁻¹ at site 1 and 75 kg N ha⁻¹ at site 2) and 50 % organic N fertilizer (digestate applied in cultivation period 2011–2012: 135 kg N ha⁻¹ at site 1 and 137 kg N ha⁻¹ at site 2 and in period 2012–2013: 98 kg N ha⁻¹ at site 1 and 108 kg N ha⁻¹ at site 2) (Table 2). At sites 1 and 2, straw management was changed in the first year of the assessment period (2011). Before the change, all straw was taken off the field to be used for energy production or animal feeding. After the change, it was left on the field and incorporated into the soil. Data on C inputs from straw and applied digestate were direct field data, and C inputs from roots (C_r) and root exudates (C_e) were calculated based on yield (Y) data, harvest index (HI), and shoot to root ratio (S:R), using the following equations (Farina et al. 2013):

$$C_r = \left(\frac{Y}{HI \cdot S/R} \right) \cdot 0.45 \quad (1)$$

$$C_e = 0.09 \cdot \left(\frac{Y}{HI} \right) \cdot 0.45 \quad (2)$$

At site 1, the mean yearly yield of the two considered crop cycles (2011–2012, 2012–2013) was 6.8 t (dry matter grain) and 3.9 t (dry matter straw), while at site 2, it was 8.0 t (dry matter grain) and 5.4 t (dry matter straw). Tier 1 and Tier 2 estimates were compared with measured GHG emissions, originating from a joint research project investigating GHG emissions from energy crops fertilized with fermentation residues. In situ measurements of N₂O and NH₃ emissions were conducted from sowing of winter wheat until the sowing of the subsequent crop for the crop years 2011–2012 and 2012–2013.

Periodic N₂O measurements were conducted one to two times per month out at three permanently installed soil collars (0.75 × 0.75 m) at each site, with higher resolution following fertilization events. Emissions of N₂O were measured by taking four consecutive 100-ml gas samples from static non-flow-through non-steady-state opaque chambers (closure time 60 min, vol. 0.296 m³; Livingston and Hutchinson 1995) and subsequently analyzed using a gas chromatograph.

N₂O fluxes were calculated based on the ideal gas law using the R package “flux 0.2-2” (Jurasinski et al. 2012), using linear regression analysis with stepwise backward elimination of outliers. The calculated flux rates were then averaged for the respective measurement day and linearly interpolated to determine total N₂O exchange.

Ammonia volatilization was measured for 2 to 5 days immediately following fertilization using the open dynamic chamber Dräger-tube method of Pacholski et al. (2006). Four stainless steel chambers were placed on pre-installed stainless steel rings (104 cm²). Chamber air was pumped through the system with a constant air flow (1 L min⁻¹), and the actual NH₃ concentration in the chamber air was directly determined in vol. ppm. Cumulative NH₃ losses were calculated by linear interpolation between measurements and in the end were summarized.

The perennial crop field trials were conducted at two peach orchards (sites 3a, 3b), located in Metapontino, the southern area of the Basilicata region in Italy, which is devoted to fruit production. They are characterized by the same rootstock and the same training system of canopy, as well as similar pedo-climatic conditions, orchard layout, and management regime. The orchard at site 3a was planted in 2006 and the orchard at site 3b in 1996 and removed after 15 years in 2011. In both orchards, a management change occurred in the eighth year after plantation (2013 for site 3a, 2004 for site 3b) from conventional to sustainable management. The conventional management regime consisted of soil tillage (site 3b), chemical weed control (site 3a), and the burning of pruning material. The sustainable management regime introduced some innovative elements, including no tillage (site 3b), mechanical weed control (grass cover mowed twice per year), the chipping of pruning residues to be left in the field, and the provision of 10 t of compost per hectare per year.

The life cycle of a fruit orchard can be divided into three main stages: the young stage characterized by low yield and grow of permanent structures, the mature stage characterized by stable high yield, and the senescence stage characterized by the decrease of yield. The farmers can decide in which stage the orchard will be removed and replanted, and usually, it happens at the end of the mature stage (Cerutti et al. 2010). For peach trees, the young stage lasts 2 years and the mature stage about 13 years. The amounts of C added to the soil during the mature stage of the orchards (i.e., as crop residues and organic fertilizers) were derived from direct field measurements: figures regarding the dry matter of senescent leaves, pruning residues, thinned fruit, and grass cover were retrieved from field sampling performed at site 3b from 2004 to 2010 (from 8th to 14th year after establishment) and at site 3a in 2013–2014 (8th and 9th year after establishment), assuming a mean C content of 0.45 t C per ton of dry matter, and a grass cover below-ground contribution of 20 % (Celano et al. 2003). The C input during the young stage of the orchard (senescent leaves and pruning material) was retrieved from an

experiment performed in a peach orchard located in the same area, with same rootstock, same training method, comparable management regime, and adapting data to the different tree density per hectare (Sofa et al. 2005). The C input from root turnover was calculated as 30 % of the trees' above-ground biomass turnover (senescent leaves, pruning material, and fruit yield) for the first 3 years and as 25 % for all other years (Buwalda 1993).

Data collected from site 3b were used to compare SOC change estimate after crop management change, performed with Tier 1 and Tier 3 methods with measurements of soil C content, performed at the beginning of the experimental period (2004) and after 7 years of management shifted to sustainable practices (2010). Each time, 30 soil samples at 30-cm depth were taken from a 1-ha field at different distances from the tree row line. SOC was determined by the potassium-dichromate oxidation procedure (Heanes 1984). Total per-hectare C stocks in the topsoil (0–30 cm) were calculated as the weighted average of SOC measured in the 30 soil samples. For site 3a, the complete CFP was calculated using primary data from the field logbook about the amount of productive inputs used to perform all agricultural operations during the orchard establishment, as well as the young and mature phase of the orchard life cycle; the SOC change of site 3a was also estimated using Tier 1 and Tier 3 methods.

2.2 Scope of the CFP assessment

GHG emissions of sites 1, 2, and 3a were calculated and included in the CFP accounting according to ISO standards 14040 (2006), ISO 14044 (2006), and ISO 14067 (2013). Our selected functional unit was not the unit of product, but the surface unit of the cropland (1 hectare), since the focus of the study was not on the environmental efficiency of the production, but on the methodology comparison (Cerutti et al. 2015). In fact, the results of Tier 1 methods are usually expressed as emissions per unit of hectare, as their first application is intended to analyze emissions from national crop production. Therefore, the results of higher Tiers and the field measurement were calculated per hectare size, in order to become comparable with Tier 1 values. However, it is important to highlight that for global issues such as food security and global warming impact of food production, GHG emission assessment and mitigation potential per unit product are often more useful than the absolute emissions per unit area (Bennetzen et al. 2012). Since CFP calculations per unit of product can take into account the variability related to yield differences, they are particularly suitable for comparative CFP studies of the same product cultivated in different locations or with different farming practices. System boundaries were fixed from cradle to farm gate, starting with production of all productive inputs, e.g., seeds, fertilizers, pesticides, agricultural machinery, and fuels (indirect emissions), and ending with the harvest

of the crop, encompassing all emissions along the production chain. Crop cultivation and processing of agricultural products can lead to multiple outputs, e.g., straw and grain from cereal harvesting or biogas and digestate from anaerobic biomass digestion. In CFP calculations, there are different methods to allocate the process emissions to different products (Benoist et al. 2012). Manure and digestate are productive input for the crop life cycle and residues (by-products) for the livestock and bioenergy life cycle. They are re-used in the same form at field (non-treated). As Rehl et al. (2012) stated, there are many ways to allocate organic fertilizer but the most logical one is the economic value. However, usually, manure and digestate are not sold by the farmers; therefore, it is difficult to determine prices because it does not exist. We followed the approach by Rehl et al. (2012) and used the open-loop allocation procedure (ISO 14067 2013, Sect. 6.4.6.3 "Allocation procedure for reuse and re cycling") and the economic indicator with the market value and assumed that the by-products are given away free of charge. Emissions from storage of organic fertilizer and on field (application of fertilizer) were considered in the crop cultivation process where these emissions occurring. The agri-footprint database (Blonk Agri-footprint BV. 2014) also considers organic fertilizer (digestate and animal manure) as residual products of biogas and animal production system, so it does not include any emissions of the biogas or animal production system, in order to avoid double counting. Conversely, for compost, the production phase was entirely included within the boundaries of the study, as it is not reused in the same form (organic urban waste), but it is the outcome of a recycling process, performed for agricultural purpose only. For the peach case study 3a, the whole life cycle of the orchard (site 3a) was included within the time boundaries, from orchard establishment until removal (15 years). This approach is coherent with the most common practice of LCA sectoral studies about fruit production from perennial tree crops (Cerutti et al. 2010; Milà i Canals and Clemente Polo 2003). The soil preparation prior to orchard establishment, the establishment and removal phase, comprising the production, and the disposal phases of materials constituting the support structure (concrete and aluminum poles, steel wire, and concrete blocks) were included in the boundaries, extrapolating data about machinery operations for the removal phase and end-of-life of trees' permanent structure from farmers' experience.

For the winter wheat case studies, direct data from two crop cycles were considered (2011–2012 and 2012–2013).

Inventory data on the amount of productive inputs (fertilizers, pesticides, fuels, machinery) were mostly retrieved directly from our on-farm experiments. GHG emissions related to the production of these productive inputs were based on the Ecoinvent database v.2.2 and v.3.0 (Ecoinvent 2013). The calculation of CO₂, CH₄, and N₂O emissions from diesel combustion was based on IPCC Tier 1 (2006b).

The considered impact category was the global warming potential (GWP)—100 years with the characterization factors from the CML 2001 method corresponding with IPCC 2007 (Ecoinvent 2013).

CFP calculations were divided into three main parts: (i) field emissions from fertilization, (ii) soil C stock change subsequent to crop management change, and (iii) all other emissions from agricultural operations. The consequences of methodological choices were analyzed by comparing the CFP results based on Tier 2 and Tier 3 approach with the reference CFP results based on IPCC Tier 1 default accounting methods.

2.3 Methodologies for the assessment of fertilization-induced field emissions

The simple IPCC Tier 1 method (IPCC 2006a) for calculating direct emission of nitrous oxide (N_2O) from managed soils simply takes into account 1 % (uncertainty range 0.3–3 %) of the anthropogenic N inputs (mineral fertilizer, organic amendments, and crop residues) at the field level. Indirect N_2O emissions take place through two pathways. The first pathway is volatilization of N as NH_3 and NO_x and their deposition onto soil and water, accounted by IPCC Tier 1 method as 10 % (0.3–3.0 % uncertainty) of kilogram N applied from mineral fertilizer and 20 % (0.5–5.0 % uncertainty) from organic amendments expressed as kilogram $\text{NH}_3\text{-N}$ + $\text{NO}_x\text{-N}$. Only 1 % of these emissions from atmospheric deposition of N volatilized from managed soils are accounted as indirect N_2O -N emissions. The second pathway of indirect N_2O emissions is leaching and runoff of N from fertilizer application and crop residues, accounted by IPCC Tier 1 method only for regions where leaching and runoff occur as 30 % (10–80 % uncertainty) expressed as kilogram N. Only 0.75 % of these emissions leaching and runoff are accounted as indirect N_2O -N emissions. This Tier 1 approach completely disregards any impact of crop type, fertilizer type, management system, and local climate conditions on the GHG emissions except for the calculation approach for leaching and runoffs which takes the regional risk for leaching into account. However, considering all or some of these agricultural characteristics in the calculation of N_2O , NO, and NH_3 emissions would more accurately reflect the heterogeneity of the environmental and management conditions occurring in agriculture. This would better allow the identification of local GHG emission hotspots and to evaluate options of reduction.

We chose a Tier 2 level modeling approach used by Bouwman et al. (2002b) to determine direct and indirect N_2O emissions and the approach of Bouwman et al. (2002a) for NH_3 volatilization. A Tier 3 level modeling approach for estimating field emissions from fertilization was not tested, since to our knowledge, it does not exist at present any approach that matches our requirements to be readily available

and easily implementable by the user. Both tested Tier 2 approaches have been validated on a large global dataset from measured agricultural field emissions encompassing 846 N_2O measurements from 126 studies, 99 NO measurements from 29 studies, and 1667 NH_3 measurements from 148 studies (Bouwman et al. 2002a; Bouwman et al. 2002b). These methods should therefore demonstrate better performance at the local scale and under different agricultural management systems than the Tier 1 methods, thus reducing the uncertainty of the estimates with respect to the global emission factors used in Tier 1 assessments (IPCC 2006a). However, implementing the Tier 2 approach after Bouwman et al. (2002a, b) requires more detailed data, as shown in Table 2. The multivariate empirical model of Bouwman et al. (2002b) classifies the parameters influencing N_2O and NO emissions into specific categories for each factor. For N_2O , the significant parameters are fertilizer type and application rate, crop type, soil texture, SOC, soil drainage, soil pH, and climate type, but only data regarding fertilizer type and application rate, SOC, and soil drainage are needed to calculate the NO emissions. The climate condition has less influence on the NO emissions, since these emissions appear to be more concentrated during the crop-growing season than N_2O emissions. During the growing season, climate condition varies less between climate types than during other seasons (Bouwman et al. 2001). The model for ammonia NH_3 emissions (Bouwman et al. 2002a) is similar to the Bouwman et al. (2002b) approach, but the significant parameters are fertilizer type, fertilizer application rate and method, crop type, soil texture, soil cation exchange capacity (CEC), soil pH, and climate type. The amount of indirect emissions can be converted to N_2O -N by multiplying the NO-N and $\text{NH}_3\text{-N}$ emissions with the default value 0.01 (based on IPCC 2006a). For reporting purposes, the total N_2O -N emissions can be converted to N_2O by multiplying the kilogram of N_2O -N by 44/28 (ratio of molecular weight of N and N_2O). For the NH_3 emissions induced by organic fertilizers (i.e., slurry and manure, digestate, poultry manure), we used the more detailed model approach by KTBL (2009) for organic fertilization to calculate $\text{NH}_3\text{-N}$ emissions, with NH_3 volatilization depending on fertilizer type, fertilizer application rate and method, daily temperature, and a binary variable indicating whether the fertilizer was incorporated within 1 h (Table 1). CO_2 emissions from the application of urea and liming were calculated based on Tier 1 IPCC (2006a) factors.

2.4 Methodologies for the assessment of emissions from soil C stock change

The default international practice about GHG accounting in the AFOLU sector (Tier 1) assumes that the soil carbon content is in equilibrium (steady state) when the last crop management change or land use change occurred more than

Table 1 Ammonia-volatilization rate (based on KTBL 2009)

Fertilizer type	NH ₃ volatilization in % of the applied NH ₄ -N				Application method-related reduction of NH ₃ emission in %				
	5 °C	10 °C	15 °C	25 °C	Drag hose (uncovered)	Drag hose (covered)	Drag shoe	Manure chisel plow	Incorporated within 1 h
Cattle slurry	30	40	50	90	8	30	30	90	80
Digestate (thickened)									
Pig slurry	10	20	25	70	30	50	60	90	80
Digestate (liquid)									
Slurry			20						
Mature manure			90						
Poultry manure			90						

20 years before the assessed time frame. In this case, it is assumed that C outputs as CO₂ emissions from organic matter decomposition equal the C inputs from organic material added to soil. As soon as the land use or management regime (tillage, soil cover, carbon input level, irrigation) changes, C input and outputs become imbalanced and either C emissions or C sequestration will occur. It may take several decades before the system returns to steady state at a new equilibrium, and the default time set by Tier 1 method is 20 years. To include the soil C change into CFP assessment, different methods are available. We tested and compared methodological approaches from Tier 1 and Tier 3, since Tier 2 national emission factors for SOC change are not always “ready available” for LCA practitioners and other existing models for both C and N cycle in soil do not match our requirement for “medium-effort modeling approaches.”

The simple Tier 1 method, explained in Chapter 5 of Volume 4 (cropland remaining cropland) of the IPCC guidelines (IPCC 2006a), requires the application of Eqs. 3 and 4. The soil organic C reference (SOC_{ref}) under native vegetation must be assigned based on six available soil types (high activity clay, low activity clay, sandy, spodic, volcanic, wetland) and nine climate regions (boreal, cold temperate dry, cold temperate moist, warm temperate dry, warm temperate moist, tropical dry, tropical moist, tropical wet, tropical montane). Three relative stock change factors further describe the site: (i) F_{LU} is related to land use (long-term cultivated, paddy rice, perennial/tree crop, set aside), (ii) F_{MG} characterizes the tillage regime (full, reduced, no tillage), and (iii) F_I describes the carbon input level (low, medium, high without manure, high with manure). These factors come with individual error ranges (between ±5 and ±50 %) and have to be defined for conditions both before and after the change in management or land use occurred.

Using Eq. 3, the soil organic carbon content before (SOC_{initial}) and after (SOC_{final}) the change can be calculated as follows:

$$\text{SOC}_t = \text{SOC}_{\text{ref}} \times F_{\text{LU}} \times F_{\text{MG}} \times F_I \quad (3)$$

The difference between the final (new equilibrium, SOC_{final}) and the initial C stock (old equilibrium, SOC_{initial}) indicates the soil C stock change in the topsoil (0–30 cm) over a period of 20 years, expressed as tons of C per hectare. This amount can be converted to atmospheric CO₂ stored in or emitted from the soil by multiplying the tons of C by 44/12 (ratio of molecular weight of CO₂ and C):

$$\Delta \text{SOC} [\text{t C year}^{-1}] = (\text{SOC}_{\text{final}} - \text{SOC}_{\text{initial}}) / T \quad (4)$$

where

T = default time period for transition between equilibrium SOC values, 20 years

The selected Tier 3 methodology consists of a simulation of the soil C turnover using the RothC model (26.3); Coleman et al. 1997). To run the simulation, the model requires inputs regarding the soil characteristics (i.e., clay content, considered depth horizon, initial SOC), climate data (i.e., monthly average temperature, cumulative evapotranspiration, and rainfall), and monthly soil C input (in tons of C per hectare), expressed as net primary production (NPP). The output of the RothC simulation of soil organic matter decomposition process is the dynamic of C fluxes between soil carbon pools (resistant and decomposable plant material, microbial biomass, and humified organic material) and the inferred CO₂ emissions in atmosphere. The RothC simulations were run for different time perspectives ($T=20, 50, 100$ years) and compared with the default Tier 1 result ($T=20$ years). Equation 4 was used as well to include soil C change in the CFP case studies using a Tier 3 method.

Before running the simulation, the initial value of the four carbon pools (decomposable, resistant, biological, humus) constituting the SOC in the RothC model was simulated using the following procedure (initialization procedure):

The C stock of each C pool was set at 0 t C ha⁻¹. The simulation was then run to equilibrium using the C input estimated for the management regime before management change. The equilibrium values of the SOC pools were used

as initial values for the simulation if the equilibrium obtained for total organic C (TOC) stocks matched the measured initial TOC; otherwise, the model was run in inverse mode to generate the required C input (CI_{req}), using the equation suggested by Mondini et al. (2012):

$$CI_{\text{req}} = CI_i \cdot \left(\frac{C_{\text{meas}} - \text{IOM}}{C_{\text{sim}} - \text{IOM}} \right) \quad (5)$$

where CI_i is the monthly C input used in the first equilibrium run, C_{meas} is the measured soil C stock to be matched, C_{sim} is the simulated soil C stock after the first equilibrium run, and IOM is inert organic matter, the small soil organic C compartment resistant to decomposition (with an equivalent radiocarbon age of more than 50,000 years), which, in absence of radiocarbon data, can be roughly estimated from total SOC using the equation provided by Falloon et al. (1998):

$$\text{IOM} = 0.049 \cdot \text{TOC}^{1.139} \quad (6)$$

With the required C input (CI_{req}), the model must be run again to equilibrium to obtain the initial value of the SOC pools.

The RothC model can only simulate heterotrophic respiration resulting from microbial decomposition of soil organic matter. However, the autotrophic respiration of plants is implicitly included as well, because the amounts of C inputs entered in the model are expressed as net primary production (NPP) of biomass, resulting from the balance between CO_2 absorbed through photosynthesis and CO_2 released through dark respiration.

The crop management changes examined in our four case studies concerned mainly the different amount of organic material returned or added to soil: In Table 3, the carbon input stock change factors selected to evaluate SOC change with Tier 1 method and the C input derived from direct field data used to implement the RothC simulation are summarized.

RothC can be considered as a reliable simulation tool of carbon turnover in soil for arable land in cool or temperate moist climates based on multiple validation campaigns (Coleman et al. 1997; Falloon and Smith 2002; Ludwig et al. 2007; Zimmermann et al. 2007), but there is a lack of model application to perennial crops (Bessou et al. 2013). Therefore, the results of RothC simulation were compared with available measurements just at site 3b and not at sites 1 and 2, due also to the unavailability of medium-long-term monitoring of SOC dynamic at these sites.

Table 2 summarizes all data required for the implementation of the four tested methodologies.

3 Results and discussion

As shown in Fig. 1, in all case studies, new SOC equilibrium after crop management change estimated using RothC model

(Tier 3) was reached in more than 20 years, the default time period assumed in the Tier 1 approach. For site 1, the SOC change at equilibrium is much lower if calculated using Tier 3 approach than using Tier 1. The Tier 3 value is outside the range of uncertainty of the Tier 1 value ($\pm 51\%$), resulting from the propagation of errors declared for each stock change factor in the IPCC (2006a) guidelines. For site 2, the equilibrium SOC change calculated using Tier 3 is also lower than Tier 1 but falls within the forecasted Tier 1 error ($\pm 51\%$).

The Tier 1 SOC change estimate is the same for the two winter wheat case studies, as the same crop, soil (high activity clay (HAC)), climate zone (cold temperate moist), and management practices were investigated, and thus, no difference between the two sites is recognizable using the Tier 1 approach. In contrast, the curves resulting from the RothC simulation are very different, because site 1 is characterized by lower soil clay content and a moister climate, which leads to a slower rate of SOC rise due to the faster decomposition rate of soil C pools. Moreover, the different amount of straw added to soil as C input in the RothC simulations is higher at site 2 than at site 1 in the considered time period 2011–2013, which leads to different values of simulated SOC change. This difference in C input is not appreciable using Tier 1 method because it is only possible to choose between the qualitative C input levels “low,” “medium,” and “high” (with or without manure), as summarized in Table 3. Therefore, finer regional variation of climate, yield, and soil texture cannot be represented using Tier 1 methodology for SOC change estimates, in the case of a crop management change.

For sites 3a and 3b, the Tier 3 SOC change at equilibrium is much higher than the Tier 1 value and outside the forecasted error range of Tier 1 ($\pm 172\%$). In the Tier 3 simulation, the succession of different peach orchard life cycles results in a fluctuation of SOC within the orchard life cycle due to the lower amount of crop residues during the establishment, the young phase, the senescence phase, and the removal of the orchard. The peak of SOC simulated at site 3a (Fig. 1) at the beginning of each orchard life cycle is due to the soil preparation with manure (60 t ha^{-1}). Moreover, for both orchards, the simulation reveals an overall increasing trend of SOC beyond the single orchard life cycle, if pursued with sustainable management practices.

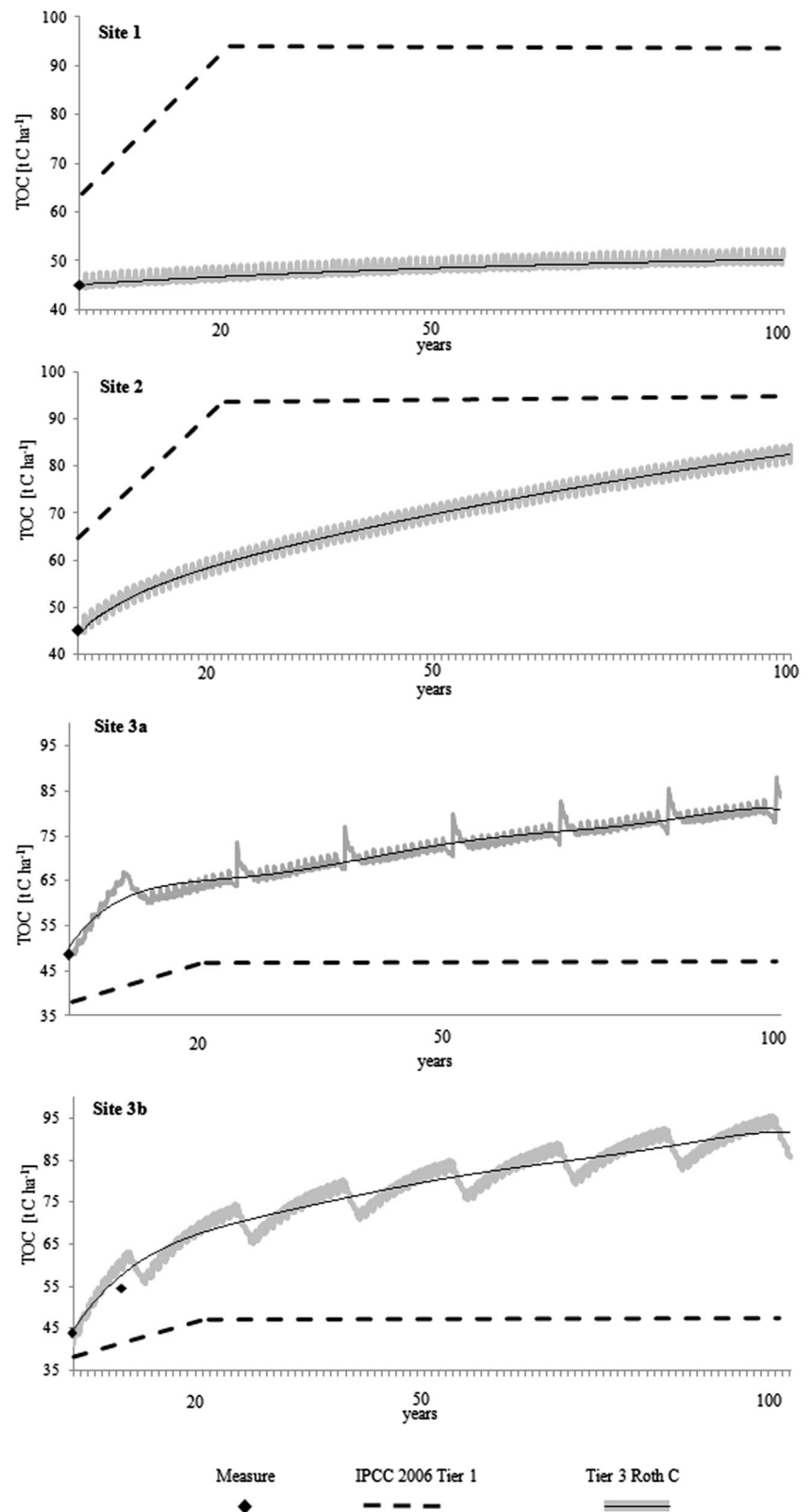
As can be noticed in Fig. 1, the comparison of SOC change measurements with estimates at site 3b reveals that Tier 1 method underestimates the measured SOC change after 7 years of sustainable management practices of 9.73 t C ha^{-1} , while RothC simulation better represents the SOC increasing trend, with an overestimation of 6.6 t C ha^{-1} . Tier 1 C input stock change factors (Table 3) do not probably reflect the real growth of soil C input after the incorporation of crop residues, compost, and grass cover into the soil. RothC overestimation could be due to the lack of consideration in the simulation of soil condition variability across the orchard hectare: the

Table 2 Characteristics of experimental sites and comparison of data requirements by tested Tier methods

	Site 1	Site 2	Site 3a–3b	Data required to estimate		
				Tier 1	Tier 2	Tier 1 Tier 2 Tier 3
Country	Germany (south)	Germany (central)	Italy (south)			
Geographical location	48° 59' N 12° 39' E	51° 00' N 11° 39' E	40° 14' N; 16° 42' E (site 3a) 40° 23' N; 16° 42' E (site 3b)			
Height above sea level (m)	431	247	16 (site 3a) 23 (site 3b)			
Crop	Wheat ^j	Wheat ^j	Peach ^k		•	•
Amount crop residues (t DM ha ⁻¹ year ⁻¹)	3.9	5.4	6.8			Qualitative
C content crop residues (% DM)	45	45	45			•
Fertilizer type	CAN ^a , digestate ^b	CAN ^a , digestate ^b	ON ^c , AS ^d , NPK ^e , CN ^f , compost ^g		•	•
Method of fertilizer application	Broadcast, incorporated	Broadcast, incorporated	Broadcast		•	•
Fertilizer amount (kg ha ⁻¹) ^h	2012: 375 ^a 2013: 388 ^a , 33,000 ^b	2012: 270 ^a 2013: 278 ^a , 32,000 ^b	2400 ^c , 200 ^d 370 ^e , 370 ^f , 80,000 ^g	•		
N content of fertilizer (%)	2012: 27 ^a , 0.45 ^b 2013: 27 ^a , 0.3 ^b	2012: 27 ^a , 0.39 ^b 2013: 27 ^a , 0.34 ^b	12.5 ^c , 21 ^d , 20 ^e , 20 ^f , 0.62 ^g			
C content of organic fertilizer (% FM)	2.5 ^b	2.5 ^b	40 ^c , 22.5 ^g			•
Soil						
Soil type (WRB classification)	Stagnic Cambisol (HAC)	Luvisol (HAC)	Eutric Cambisol (HAC)		•	•
Soil texture	Loamy sand	Silty clayey loam	Sandy loam		•	•
Soil bulk density (g/cm ³)	1.7	1.5	1.5 (site 3a) 1.6 (site 3b)		•	•
pH value	5.1	7.4	7.1 (site 3 a) 8.1 (site 3 b)		•	•
SOC before change	0.5	0.5	1.0		•	•
Soil drainage	Good	Good	Good		•	•
Climate						
Climate region	Temperate	Temperate	Temperate		•	•
Precipitation (cumulative yearly in mm) ⁱ	957	582	525	•	•	Monthly value
Temperature (yearly in °C) ^j	8.3	9.6	16.4		Specific days	Monthly value
Evapotranspiration (cumulative yearly in mm) ^j	611	568	1262	•	•	Monthly value
Management			Converted to no tillage during the experimental period		•	•
Tillage regime						

^a CAN calcium ammonium nitrate^b digestate fermentation of biomass from energy crops and animal slurry^c ON organic nitrogen fertilizer^d AS ammonium sulfate^e NPK nitrogen (N) + phosphorus (P) + potassium (K) compound^f CN calcium nitrate,^g Compost with 40 % mineralization efficiency^h Cumulative amount of fertilizers distributed within the time boundaries of the studyⁱ Average values over the experimental periods^j Winter wheat (*Triticum aestivum* L.)^k Peach (*Prunus persica*)

Fig. 1 Simulations of SOC change subsequent to the shift to sustainable crop management, performed using IPCC (2006a) Tier 1 approach and using RothC 26.3 model initialized with measured SOC before management change (the *gray line* represents monthly simulation and the *black one* yearly average)



variable soil moisture with the distance from the tree line due to drip irrigation and the concentrated distribution of compost and roots along the tree line (Montanaro et al. 2012).

In Table 4, the yearly rates of SOC changes are reported for different time horizons (20, 50, 100 years). Generally, it can be stated that with a longer time horizon, the yearly rate of SOC

Table 3 Selected C input stock change factors selected to calculate SOC change with Tier 1 method and the C input derived from direct data used to implement RothC simulation

Management practices		Tier 1 C input stock change factor	C input Tier 3 (t C ha ⁻¹ a ⁻¹)			
			Site 1	Site 2	Site 3a	Site 3b
Winter wheat before change	Straw removed from field + digestate addition	Medium 1.00 <i>Representative for annual cropping with cereals where all crop residues are returned to the field. If residues are removed, then supplemental organic matter (e.g., manure) is added. Also, it requires mineral fertilization or N-fixing crop in rotation.</i>	2.22	2.24		
Winter wheat after change	Straw incorporated in soil + manure addition	High with manure 1.44 (Error ±13 %) <i>Represents significantly higher C input over medium C input cropping systems due to an additional practice of regular addition of animal manure.</i>	4.02	4.67		
Peach orchard before change	Pruning residues burned, chemical weed control (site 3a), and tillage (site 3b)	Low 0.95 (Error ±13 %) <i>Low residue return occurs when there is due to removal of residues (via collection or burning), frequent bare fallowing, production of crops yielding low residues (e.g., vegetables, tobacco, cotton), no mineral fertilization, or N-fixing crops.</i>			1.8	1.8
Peach orchard after change	Pruning residues incorporated in soil, mechanical weed control, no tillage, compost addition	High without manure 1.04 (Error ±13 %) <i>Represents significantly greater crop residue inputs over medium C input cropping systems due to additional practices, such as production of high-residue-yielding crops, use of green manures, cover crops, improved vegetated fallows, irrigation, frequent use of perennial grasses in annual crop rotations, but without manure applied</i>			5.8	6.8

change, expressed as CO₂ removed from atmosphere, decreases, since SOC change is always faster during the first years after disturbance. This aspect has already been highlighted in Petersen et al. (2013), where they suggested using a 100-year time horizon when simulating SOC change for CFP studies, based on a 100-year GWP calculation. However, it is difficult to elaborate predictions in such a long term, as many factors characterizing the agricultural sector (e.g., land use, cropping systems, and management regimes) are usually defined by highly volatile framework conditions (e.g., consumer demand, economic trends, societal transformation, and public policy). For agricultural land use decision-making, even 20-year continuous land use of the same kind is not common and LUC should be considered at a more reasonable time horizon. Furthermore, when changing the cultivation system each year, the effect of management change on the SOC content is not stable and the uncertainty of the results is very high. In order to more consistently compare Tier 1 and Tier 3 methods, the yearly SOC change value derived from

20-year RothC simulation has been used and included into CFP of the examined case studies (Fig. 2).

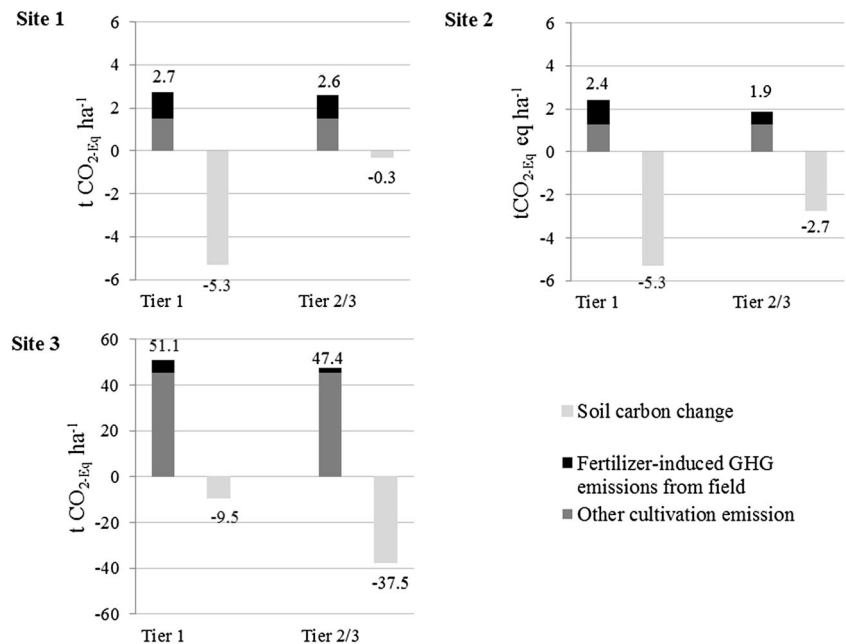
Figure 2 shows the CFPs of sites 1, 2, and 3a and the relative contribution of the three different GHG emission categories. The CO₂ removals from SOC change are reported separately as prescribed by ISO 14067 (2013), because of the temporary character of CO₂ storage in soil. For sites 1 and 2, the CFP represents the sum of all GHG emissions and removals during a 1-year crop cycle, while for the site 3a CFP, the entire 15-year peach orchard life cycle was taken into account, with the last 8 years of management regime shifted to sustainable practices. For CFP calculation of annual crops, the whole crop rotation and the crop rotation-related effects should be taken into consideration as stated by Brankatschk and Finkbeiner (2015). Especially, crop residues can have a great influence on the crop rotation effects, since crop residues remaining on the field affect the subsequent crop through influencing the physical, chemical, and biological soil properties and improving the soil fertility. The nutrients (N, P, K)

Table 4 Results of SOC change, expressed as CO₂ removed from atmosphere, calculated with different time horizons and different Tier approaches for the experimental sites

Experimental site	Assessment approach	Time horizon (years)	SOC change at equilibrium (t C ha ⁻¹)	SOC change (t CO ₂ ha ⁻¹ a ⁻¹)
1	Tier 3 RothC	1		-1.13
		20		-0.33
		50		-0.26
		100	5.18	-0.19
			28.8 (±14.7)	-5.29
2	Tier 3 RothC	1		-7.80
		20		-2.74
		50		-1.87
		100	38.15	-1.40
			28.8 (±14.7)	-5.29
3a	Tier 3 RothC	20		2.99
		50		2.63
		100	55.2	2.03
			7.4 (±12.7)	-1.35
				-9.91
3b	Tier 3 RothC	7		-5.36
		20		-2.94
		50		-1.61
		100	43.87	-1.35
			7.4 (±12.7)	-1.35

remaining in crop residues on field can be used by the subsequent crop and can result in a reduced fertilizer dose for the subsequent crop. This problem can be accounted in the CFP of the subsequent crop in two ways: allocating the respective environmental burdens to the subsequent crop or a credit can be given for the current crop if a reduced fertilizer dose is recommended for the subsequent crop. So far, there is no agreement about a uniform approach on how to include the

effects of the crop rotation in the CFP calculation of an annual crop (Brankatschk and Finkbeiner 2015). We tried to include the crop rotation effect for the winter wheat crops by using the real crop cultivation data provided by the researchers from the experimental sites. The amount of farming operating material for each crop applied at field was calculated in advance in consideration of the local pedo-climatic conditions, the characteristics of the previous crop (overall fertilization strategy

Fig. 2 Comparison of CFP calculated using the Tier 1 and Tier 2/3 approach for the three case studies (for sites 1 and 2, mean values from two cultivation years at each site, site 3 values are totaled up over 15 years). SOC change is calculated in a 20 years' time horizon

for the crop rotation), and the amount of nutrients available in the soil (provided by the soil samples). Furthermore, the real obtained yield and nutrient content at each site were used to calculate the amount of SOC added to the field through crop residues and digestate.

For site 1, the choice of either Tier 1 or Tier 3 for SOC change estimation is a relevant decision, as SOC change calculated with Tier 1 corresponds to 194 % of all other CFP emissions (the agro-ecosystem is a C sink), while the Tier 3 estimate amounts to approximately 13 % of all other emissions. For site 2, the Tier level selected for SOC change estimation is less crucial, as in both cases, the agro-ecosystem is considered to be a C sink, but the benefit calculated by Tier 3 is lower (145 against 221 % of all other CFP emissions offset with Tier 1). In site 3a, the use of the Tier 3 method resulted in a more realistic value of SOC change than Tier 1. During 8 years of sustainable management practices, 81 % of all other CFP emissions can be offset through soil C storage, compared to only 19 % estimated with Tier 1. Pursuing a sustainable management regime, the Tier 3 simulation reveals that the subsequent peach orchard life cycle would be a C sink, storing 152 % of the emissions from agricultural operations and field emissions from fertilization in the soil.

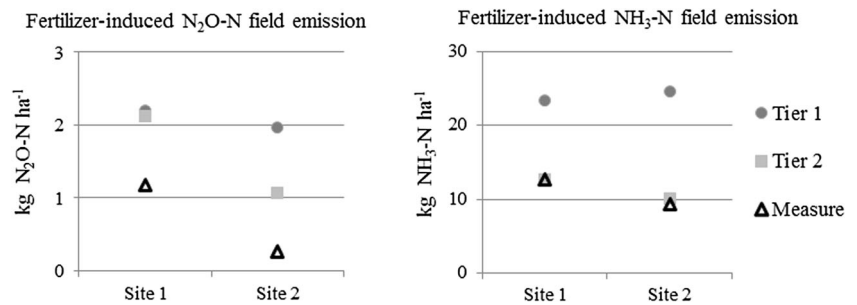
For the annual crops, field emissions from fertilizer application are an important factor, accounting for almost 50 % of the emissions calculated using Tier 1 for sites 1 and 2. In contrast, for the perennial peach crop, emissions from fertilizer application contribute around 10 % (Fig. 2). In all case studies, the Tier 2 estimates of fertilizer-induced field emissions are lower than the Tier 1 estimate (−9 % for wheat at site 1, −46 % for wheat at site 2, and −65 % for peach at site 3) and within the uncertainty range of −70 to +325 % reported for the default global emission factor from Tier 1. The consequence of using a higher Tier (Bouwman et al. 2002b) to calculate field GHG emissions from fertilizer application is a CFP reduction of 4 % for wheat production at site 1, 21 % for wheat production at site 2, and 7 % for peach production at site 3a. As the yield from annual crops is strictly dependent on nutrient availability and weather conditions during a relatively short cultivation period, the fertilizer management system is often more intensive for the short annual crop cycle than for perennial crops. Consequently, the fertilizer management system has a larger influence on overall field emissions for annual crops than for perennial crops, which feature considerably lower fertilizer input throughout their entire life cycle.

As reported in the IPCC (2006a) guidelines, the global default values (Tier 1) are, in some cases, adequate to determine fertilizer-induced field emissions—as confirmed by our wheat case study (site 1). However, in most cases, these factors should be specified based on environmental conditions (climate and soil characteristics) as well as on crop management conditions (fertilizer type, fertilizer application method, and rate) as in our second wheat (site 2) and our peach (site 3) case study.

To evaluate these findings, we compared the Tier 1 and Tier 2 estimates for N_2O and NH_3 emissions from the two winter wheat case studies with field-measured GHG emissions (Fig. 3). For both sites and both gases, the Tier 1 and 2 calculations overestimated the measured fluxes. However, for NH_3 -N emissions, Tier 2 estimates only deviate 1 and 10 % from measured data of site 1 and site 2, respectively. In contrast, Tier 1 calculated NH_3 -N emissions are 87 and 168 % higher than measured emissions for site 1 and site 2, respectively. Tier 2 estimates of fertilizer-induced N_2O -N field emissions are less accurate than estimates for NH_3 -N, but more accurate than Tier 1 estimates. As Firestone and Davidson (1989) have stated, the microbial processes of denitrification and nitrification are the dominant sources of gaseous N emissions from agricultural soil systems. Many factors associated with crop, soil, water, climate, and fertilizer management can influence soil turnover processes at all levels, e.g., organic matter decomposition, denitrification, and nitrification. Consequently, the heterogeneity of soil and weather conditions hamper a sufficiently accurate representation of N_2O , NO, and NH_3 emissions from a field using a model. As presumed, the Tier 2 estimates of fertilizer-induced N_2O -N and NH_3 -N field emissions were closer to the measurements than the Tier 1 estimations. Especially, the NH_3 -N field emission estimates were very close to the measurements results. Most NH_3 -N emissions on field arise from organic fertilizer application, but the modeling approach from Bouwman et al. (2002a) does not distinguish between different organic fertilizer types, but the used KTBL (2009) calculation method for organic fertilizer takes the fertilizer type, the temperature during application of the organic fertilizer, and the application method into account. Therefore, through combining the two modeling approaches (for mineral fertilizer Bouwman et al. (2002a) and for organic fertilizer KTBL (2009)), the accuracy of the modeling results could be increased.

Comparing modeling data with measurements can be problematical since measured data and modeled data have also a risk of uncertainty. As Bouwman et al. (2002c) pointed out in their study, the amount of N_2O and NO emissions is influenced by the measurement technique, the length of measurement period, and the frequency of measurements per day. For N_2O emissions are longer measurement periods (>300 days) and intensive measurements (≥ 1 per day) better to detect the fertilization effect on the N_2O emissions. However, for NO emission, no significant differences in measurement frequency classes could be found. The frequency of measurement and continuity is a sensitive factor to detect the fertilization effect on the N_2O emissions. In our case, N_2O measurements were conducted one to two times per month with higher resolution following fertilization events; therefore, they are not continuous and include a risk of uncertainty. To reduce this uncertainty, the N_2O fluxes arising in the periods between the measurements were calculated using linear regression analysis as

Fig. 3 Comparison of fertilizer-induced N_2O -N and NH_3 -N emissions on field calculated using Tier 1 and 2 approach and measured data, mean values from two wheat cultivation periods at each site



explained in the Sect. 2.1. Ammonia volatilization was measured for 2 to 5 days immediately following fertilization. On both sites (1 and 2), the experimental length exceeded the 300 days and, correspondingly, our measurement period implying a low risk of uncertainty. The considered time frame for data collection can influence the N_2O emission result. The emissions that occur during mineralization of organic matter after harvest can be charged to the harvested crop or to the subsequent crop. Both modeling approaches (Tiers 1 and 2) are based on the same dataset of measurements, with a determined level of uncertainty (Bouwman et al. 2002a, b). However, the Tier 1 modeling approach only considers the amount of N applied and is more suitable for global- or national-scale calculation where the variability of environmental- and management-related factors is not appreciable for the different regions (IPCC 2006a). Since the Tier 2 modeling approach introduces more parameters to account for the heterogeneity of local pedo-climatic and management conditions, it is more suitable to represent field emissions at farm or project scale.

Gabrielle et al. (2006) also compared different modeling approaches for N_2O emission calculation from winter wheat on regional scale. We come to the same conclusion as Gabrielle et al. (2006) that in the case of fertilizer-induced field emissions, a higher Tier approach with a focus on the aforementioned regulating factors, especially regional environmental conditions, could therefore be used to adequately detect mitigation potentials. As Fig. 3 shows, our suggested Tier 2 approach can be a good solution to estimate fertilizer-induced field NH_3 -N emissions, as it takes these regional environmental and management conditions into account. However, the results for fertilizer-induced field N_2O -N emissions modeling with the different Tier approaches were not convincing; therefore, we recommend to continue testing at more sites and with more crops to confirm our hypothesis.

4 Conclusions

The choice of the methodological approach (Tier level) can considerably affect the CFP of agricultural products. Therefore, sufficient transparency is required to inform relevant parties about possible error and shortcomings introduced

by the selected method when applied to a case study. In this paper, we identified appropriate, readily available, assessment methods at the Tier 2 and Tier 3 level with medium efforts for stakeholders and explored the consequences of these methodological choices on the CFPs of annual and perennial crops for field GHG emissions from crop cultivation.

Only few site-specific data are needed to apply these higher Tier approaches, which can be used to improve the accuracy of the estimate of land-based GHG emissions from fertilization and soil C change, thus supporting the assessment of the agricultural mitigation potential and the development of GHG reduction plans at farm level.

The results for fertilizer-induced field emission calculation were consistent among the three case studies: using the higher Tier (Tier 2) led to lower estimated field emissions from fertilization at two sites and to almost equal emissions at one site compared to results obtained with the Tier 1 approach and to a more reliable estimate in agreement with field measurements. Based on our results, we suggest the following recommendations: For annual crops, a higher Tier approach is particularly important when estimating fertilizer-induced field emissions, whereas for perennial crops, it has a minor impact on the CFP. However, we cannot draw general conclusions on the efficacy of default emission factors for annual and perennial crops from this limited amount of data; therefore, further studies are needed to confirm our findings.

Regarding soil C stock change, important differences were found between results calculated with Tier 1 and Tier 3 methodologies. Using the Tier 1 approach can lead to wrong estimates due to equivocal interpretation of the carbon input stock change factor (qualitative description of the amount of organic material entered to soil) and to the lack of specification of local pedo-climatic conditions. Tier 3 RothC simulations can constitute a valid alternative, as local primary data about climate, soil features, and carbon input can be entered in the model; RothC simulation of SOC change after the modification of a crop management routine showed more reliable results when tested against available measurements than Tier 1 estimates. A more frequent SOC monitoring campaign would be useful to further test the model's performance and calibrate it to orchards' features. The present study has underlined the relevance of SOC change from crop management change on

CFP of perennial crops, which cannot be always adequately represented using a Tier 1 approach. Concerning annual crops, crop rotations were not included in the RothC simulation, as SOC change after land use change (crop change) was not included in the scope of the assessment. However, the influence of SOC change on CFP of 1-year crop cycle could be strongly related to the long-term SOC dynamic, subsequent to crop choice and to the management regime, which determine the amount of organic residues returned to soil. Thus, for annual crops, a simulation approach is also advisable to evaluate SOC change as the default Tier 1 does not allow to represent the change of different crops in the rotation. Further investigation efforts are needed in this direction. Similarly to what was done in this paper for *default carbon input level stock change factors*, it would be interesting to assess how the *default land use stock change factors* (long term cultivated, paddy rice, perennial crops, set aside) of Tier 1 method influence the performance of SOC change estimate with respect to higher Tier approaches.

The outcomes of the present paper suggest that it is necessary to foster more awareness and consensus within LCA practitioners and policy-makers about the importance of including regional field emissions into CFP of agricultural products, as it can considerably affect the results of the analysis. Moreover, it is recommendable to use modeling approaches for field emissions' estimate, taking into account local pedoclimatic and crop management conditions, because this can significantly improve the reliability of GHG accounting for agriculture at farm level.

The higher-tiered methodologies for the calculation of field emissions from fertilization and SOC change require little additional effort compared with default Tier 1 methods, and thus, their practical application is advisable. However, the development of user-friendly, crop-specific tools underpinning these modeling approaches could more efficiently increase the usefulness of CFP for agricultural sustainability assessment at farm and regional landscape level.

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